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CALCULATIONS FOR EXPLOSIVE MAGNETIC GENERATORS

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This is a translation of a Soviet paper which develops generalized criteria for optimum design of an explosive magnetic generator.

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INTRODUCTION

Studies on techniques for pulsed compression of magnetic fields, with the resultant high pulse power generation, were actively pursued in the late 1960's and early 1970's both here and abroad. In recent years the interest in these techniques appears to have dwindled, notably in the U.S. A recent search by the Smithsonian Science Information Exchange, in fact, indicates no current U.S. research program under way on explosive compression of magnetic fields.

In contrast, a continuing study of explosive cumulation is being maintained in the USSR, in particular under the direction of Bichenkov and Lobanov at Novosibirsk. These authors have published a series of papers on theoretical and experimental aspects of explosive compression, in which both coaxial and planar sandwich geometries have been investigated.

The most recent paper on the subject, published by Lobanov early in 1976, is also the most comprehensive in its development of design criteria for such explosive generators. The treatment develops the criteria based on several variants of load type and energy coupling mode, without specifying any particular geometry of the explosively-driven conductors.

The full translation of Lobanov's paper is accordingly given herewith, to emphasize the Soviets' continuing attention to an extremely high power pulse technique which seems to have been abandoned elsewhere.

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Lobanov, V. A. (Novosibirsk). A method for calculating explosive magnetic generators. Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki, no. 1, 1976, 120-127.

Abstract:
A method is described for calculating explosive magnetic generators, which determines the interrelations among circuit parameters which yield maximum delivered power, assuming a time-varying ohmic load. By way of example an analytical calculation is given for coupling planar generators to a load whose resistance rises linearly with temperature. The feasibility is shown in principle of developing such a generator, in which the power delivered to an ohmic load R(t) is time-variant in a selected manner. Pulse shape, power and energy delivered to the load are analyzed for various generator circuit parameters.

1. Explosive magnetic generators (EMG) operate on the principle of rapid compression of magnetic flux by the force of explosion; they are among the most powerful sources of pulsed currents [1 - 4]. In studying EMG particular attention is paid to their power characteristics, which either are aimed at obtaining maximum power in the active load [5] or at achieving the maximum conversion of explosive energy into electromagnetic energy by increasing the generator efficiency [6]. An analytical solution of such problems can only be obtained for a constant load; for R_0 with a randomly changing resistance the problem is solved numerically by computer. The use of EMG in plasma experiments [7] for obtaining great magnetic pressures in isentropic compressions of materials [8] or for other physical experiments, poses several other problems in addition to those related to power: matching the generator to various loads and obtaining pulses of current, power and magnetic pressures which are time-variant in a selected manner.

An EMG operating with a lumped active load is analyzed within the framework of an electrical model in which the EMG is presented as a decreasing inductance $L_1(t)$ coupled to resistance $R(t)$ and inductance L_2 (Fig. 1). With the start of the magnetic flux compression ($t=0$) current I_0 flows through the generator. It is assumed that magnetic flux losses in the generator are much lower than in the load.

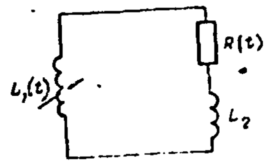


Fig. 1

Based on the law of induction we may describe the current in the generator by the following equation: $d\ln I=(1-\rho)d\ln L,\ L=L_1(t)+L_2.$
In addition to inductance L the current depends on the dimensionless function ρ (dimensionless circuit resistance), determined by the resistance $R(t)$ as well as by dL/dt as a function of EMG design:

$$\rho(t)=-\frac{R(t)}{dL/dt}. \quad (1.1)$$

In certain cases the formula for the current may be obtained in explicit form, whenever the behavior of $\rho(t)$ is given. Then, by varying dL/dt, we may obtain for one and the same value of $R(t)$ a different time dependence $\rho(t)$ so that current of different forms can flow in the load.
The dependence of generator current on the dimensionless combination of circuit parameters (1.1) may be used to solve many problems, when by conditions of the experiment the variation in $R(t)$ is preassigned, i.e., determination of generator inductance for optimum use of explosive energy; and determination of inductance at which current pulse, power and energy in the load vary in time in a selected manner. In order to solve these problems we integrate (1.1), taking into account the concrete conditions of the problem and the

behavior of R(t). In this case we assume $\rho(t)$ to be any convenient function that ensures the solution of the problem. EMG's are the only source of energy that can ensure a solution of the above problems for any random active load. The parameter ρ, whose physical meaning is the ratio of the compression time τ_0 to the time of magnetic flux relaxation τ_1 =L/R, is sometimes interpreted as inverse magnetic Reynolds number [7].

2. Let us apply the proposed method for finding the optimal (with respect to the use of explosive energy) inductance of an EMG operating into a resistive load that varies under heating. In this sense an optimal generator is one in which the greatest part of the explosive charge energy is converted into electromagnetic energy. The condition for optimization was defined in [6] and is fulfilled when power, developed by deformation of the circuit with current, is equal in any cross-section of the generator to the maximum power produced by detonation of the explosive charge, i.e.,

$$-\frac{I^2}{2}\,dL/dt = kqS(x)\,D, \tag{2.1}$$

where q is the explosive energy per unit volume; S(x) is the cross-sectional area of the explosive charge; x(t) is the moving coordinate of the detonation front; D is the speed of the explosive detonation; and k is the conversion coefficient for explosive energy into electromagnetic energy.

For a linear change of resistance with rising temperature, $R = R_0(1+\alpha T)$ under Joule heating we have:

$$\frac{dR}{dt} = \frac{R_0\alpha}{C}\,RI^2, \tag{2.2}$$

where α is the temperature coefficient of resistance; C is the net specific heat capacity of the load; and R_0 is the initial value of resistance.

Equations (1.1), (2.1), (2.2) determine the dependence of resistance on time, $R(t) = R_0\left(1 + \frac{2\alpha k q D}{C}\int_0^t S(\xi)\rho(\xi)\,d\xi\right)$
and the inductance of the optimum generator,

$$L_1(t) = L_1(0) - \int_0^t \frac{R_0}{\rho(\tau)}\left(1 + \frac{2\alpha k q D}{C}\int_0^\tau S(\xi)\rho(\xi)\,d\xi\right)d\tau. \qquad (2.3)$$

3. With respect to explosive charge energy, we now find the optimal width of busbars, and current, power and behavior of the load in time when firing a planar EMG whose resistance increases linearly with temperature. The inductance of the planar generator is described by

$$L_1(t) = L_1(0) - \int_{-l}^{-l+Dt} \frac{4\pi b}{y(x)}\,dx. \qquad (3.1)$$

It is assumed that the magnetic field in the generator is homogeneous, i.e., the distance between the busbars (2b = const) is smaller than the width of the busbars 2y(x) which changes over the length of the generator x(t). The busbars close with a speed equal to the detonation rate D. The full length of the generator is denoted by ℓ. Coordinate origin is at the point where busbars connect with the load. Explosive charge cross-section with a uniform thickness 2δ is $S(x) = 4\delta y(x)$.
It follows from eqs. (2.1), (3.1) that current behavior in an optimum planar generator coincides with the changes in the width

of the busbars that compress the magnetic field, i.e.,

$I = I_0 y/y_0,\ y_0 = y(-l).$ This is explained by the fact that when optimizing the EMG at k= const, the store of kinetic energy of any conductor element, as obtained from the explosive charge of constant thickness, remains fixed over the length of the generator. To obtain the optimal k value it is required that the force acting on the conductor from the magnetic field in the decelerating path 2b = const will remain unchanged along the explosive charge. This means that in a generator with variable busbar width the linear current density at the magnetic field compression front remains uniform.

For $\rho = \rho_0 \exp(\beta t)$, where β = const, and using the above equations, we find the optimum layout of busbars:

$$y(x) = \frac{y_0 \exp\left(\beta \frac{x+l}{D}\right)}{\sqrt{1 + \frac{B}{2\beta}\left[\exp\left(2\beta \frac{x+l}{D}\right) - 1\right]}}, \quad B = \frac{16\alpha k q \delta y_0 D \rho_0}{C}$$

as well as the increase in load resistance,

$$R(t) = R_0 \sqrt{1 + \frac{B}{2\beta}[\exp(2\beta t) - 1]}.$$

If R(t) and I(t) are known, we can determine power $P = I^2 R$ delivered to the load. In sufficiently long generators the nature of changes in busbar width and the values of power, current and resistance depend to a large extent on the parameter β. For $\beta > 0$ and $t \to \infty$ the busbar width and the current tend to limit values:

$$y(x) = y_0 \sqrt{2\beta/B},\ I = I_0 \sqrt{2\beta/B}$$

Resistance and power increase exponentially:

$$R \to R_0 \sqrt{B/2\beta} \exp(\beta t),\ P \to R_0 I_0^2 \sqrt{2\beta/B} \exp(\beta t).$$

For $\beta < 0$, the resistance cannot exceed $R_0\sqrt{1-B/2\beta}$, and the busbar width, power and current approach zero. If the active load is constant ($\alpha = 0$), $y(x) = y_0 \exp\left(\beta \frac{x+l}{D}\right)$, which corresponds to the result obtained in [6].

A qualitatively different result occurs when a planar generator operates under a constant $\rho = \rho_0$. In this case the busbar width (and current) decrease,

$$y(x) = \frac{y_0}{\sqrt{1 + B\frac{x+l}{D}}},$$

while the ohmic load increases according to another time law,

$$R(t) = R_0\sqrt{1+Bt}.$$

The decrease in busbar width is dictated by the fact that with increasing resistance the condition ρ = const is met when $-dL/dt = 4\pi bD'y(x)$ increases. Hence the condition requires a tapering of the generator busbars. With this geometry of busbars, during the period of flux compression the energy delivered to the load is: $W_1 = \int_0^{l/D} RI^2 dt = \frac{C}{\alpha}\left(\sqrt{1+B\frac{l}{D}} - 1\right)$

and the energy of the explosive charge, $Q = \int_{-l}^{0} 4q\delta y(x)\,dx = \frac{C}{2\alpha k\rho_0}\left(\sqrt{1+B\frac{l}{D}} - 1\right).$

From the relation $\frac{W_1}{Q} = 2k\rho_0$ (3.2)

we can see that for $\rho_0 > 1/2$, energy developed in the resistance may be larger than energy contained in the explosive charge. There is an explanation for this apparent contradiction.

Power $-\frac{I^2}{2}\frac{dL}{dt}$ is delivered to the active load and causes an increase in magnetic field energy, and the energy equation has this form:

$$-\frac{I^2}{2}\frac{dL}{dt} = RI^2 + \frac{d}{dt}\left(\frac{LI^2}{2}\right). \qquad (3.3)$$

From this we see that with $R > -\frac{1}{2}\,dL/dt$, energy of the magnetic field is released in the resistance in addition to explosive charge energy, hence the relation (3.2) makes sense.

By integrating (2.1) for a known cross-section S(x) of the explosive charge we can determine an inductance of the EMG, which can develop a power $P=I^2R$ varying in time in a selected manner:

$$L_1(t) = L_1(0) - \int_0^t \frac{2kqS(\xi)R(\xi)}{P(\xi)}\,d\xi$$

4. We now examine the problem of EMG optimization in terms of releasing the maximum energy in a variable active load.

It can be assumed that depending on the R(t) value in a given layout, we may obtain a release of energies of different magnitudes. With $R \to 0$, $W \to 0$; but with $R \to \infty$ (because of rapid flux losses) we cannot expect to have an energy that would significantly exceed the initial energy of the magnetic field $(W_0 = L_0 I_0^2/2)$.

For R_0 = const and $\rho = \frac{1}{2}$ we would have $W_1 = W_0 \ln(L_0/L_2)$ [5].

In [7] experiments are described on switching an EMG to a special plasma load, and a calculation of resultant energy is given for the case when the inverse magnetic Reynolds number is constant.

It would be more interesting to find that relationship among EMG parameters for which, during operation of the EMG and under a randomly changing ohmic load, the maximum energy is released. This problem can be completely solved when $\rho = \rho_0 = \text{const}$.

Then we obtain for the current: $I = I_0 \lambda^{1-\rho_0}$;

and for the energy in the resistance: $W_1 = \int R I^2 dt = W_0 \frac{2\rho_0}{2\rho_0 - 1} (1 - \lambda^{1-2\rho_0})$;

and the value for the magnetic field energy: $W_2 = L I^2/2 = W_0 \lambda^{1-2\rho_0}$,

where $\lambda = L_0/L(t)$, $\lambda_0 = L_0/L_2$ are the instantaneous and overall coefficients of generator mismatch; $L_0 = L_1(0) + L_2$ is the initial circuit inductance.

In Fig. 2 the value of $E=W_1/W_2$ as a function of ρ_0 for $\lambda = 100$; curves 1 and 2 show that with the preset value of λ_0 there is only one value for ρ_* when energy reaches its maximum magnitude E_* ($E_*(\rho_0, \lambda_0)$, curve 3). The value ρ_0 is determined from the solution of transcendental equation

$$\frac{dE}{2d\rho_0} = -\frac{1}{(2\rho_0 - 1)^2} + \frac{\lambda_0^{1-2\rho_0}}{(2\rho_0 - 1)^2} + \frac{2\rho_0}{2\rho_0 - 1} \lambda_0^{1-2\rho_0} \ln \lambda_0 = 0. \qquad (4.2)$$

Introducing the variable $\xi = (1 - 2\rho_*) \ln \lambda_0$,

equation (4.2) to determine the optimum values of ρ_0 and λ_0 can be reduced to this system of equations:
$$\begin{cases} 2\rho_* = 1 - \xi/\ln \lambda_0; \\ 2\rho_* = \dfrac{1 - \exp(-\xi)}{\xi}, \end{cases}$$

where λ_0 is a paramcter. By assigning the λ_0 value, a graphical method (Fig. 3) is employed to find the values $\rho_0(\lambda_0)$ from (4.3).

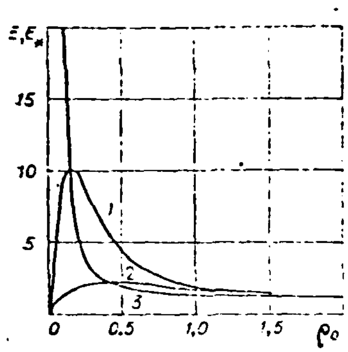


Fig. 2

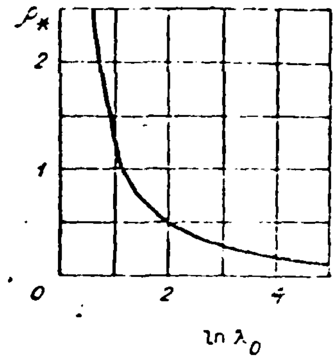


Fig. 3

An analysis of E_* and $W_* = W_2/W_0$ shows that large energy release in the load may take place even with small ρ_* values. With $\rho_* \gg 1$ energy in the resistance is close to the initial magnetic field energy.

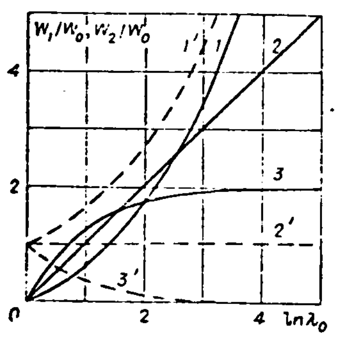
In generators with $\rho_0 = \rho_*$ and a low tuning [coupling?] coefficient $\lambda_0 < e^2$, most of the energy is released in the resistance. At $\lambda_0 = e^2$ the energy developed in the load towards the end of the generator operation is twice as large as the energy stored in the magnetic field. In generators with a large tuning coefficient $(\lambda_0 > e^2)$, the energy stored in the magnetic field exceeds the energy released in the resistance.

From equation (4.1) it follows that energy developed in the resistance as a function of λ_0 has no maximum for a preset value. At $\rho_0 < \frac{1}{2}$, the energy W_1 increases monotonically with λ_0 up to the value of $W_1 = W_0 \frac{2\rho_0}{1-2\rho_0} \lambda^{1-2\rho_0}$.

When $\rho_0 > \frac{1}{2}$ the energy in the load increases with increasing λ_0 up to a limiting value of $W_1 \approx W_0 \frac{2\rho_0}{2\rho_0 - 1}$.

Let us investigate the operation of an EMG at $\rho_0 = \frac{1}{2}$. From the energy equation (3.3) we can see that at $R(t) = -\frac{1}{2} dL/dt$ the magnetic field energy in the generator remains constant, and all the power developed from the current circuit deformation by external forces is used for heating up the conductors, i.e., $W_2 = W_0$, $W_1 = W_0 \ln \lambda_0$.

In Fig. 2 the vertical line corresponds to such release of E; the line passes through $\rho_0 = 0.5$. Under such conditions of operation less energy is released in the resistance than is released for the optimal $\rho_* \neq \frac{1}{2}$. In Fig. 4, the development of energy in the resistance is shown in solid lines, that in the magnetic field in dotted lines, at preset values as a function of



$1,1' - \rho_0 = 0,25$; $2,2' - \rho_0 = 0,5$; $3,3' - \rho_0 = 1$

Fig. 4

Hence the computation of EMG parameters, when the EMG develops in a resistance R(t) an energy W_1, proceeds as follows. Taking into account the initial energy W_0 we preset the ratio W_1/W_0 and from curve 3 in Fig. 2 we find the optimal value for ρ_* ; in Fig. 3, the value λ_0 corresponds to the optimal value of ρ_0 . From the determined value for ρ_* and the preset R(t), by integrating equation (1.1), we find the required change in generator inductance.

A study of EMG operation thus shows that the selection of certain relationships among its parameters (explosive charge, deceleration path, load resistance, etc.) allows us to do the following: 1) to determine the optimal inductance (with respect to the explosive energy use) of an EMG, coupled to a resistance which varies with temperature; 2) to design such generators which can develop load powers that vary in time in a selected manner; 3) to find for an arbitrary load R(t), assuming ρ = const, that inductance for which the maximum of energy is released.

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